1999 ASME Fluids Engineering Division Summer Meeting
FEDSM'99
July 18 - 23, 1999

FEDSM99-????

FULL-SCALE TEST OF A NON-PLUGGING BUBBLER USED IN LARGE TANKS CONTAINING HIGH YIELD STRESS SLURRIES

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ABSTRACT

As a follow-up to a bench-top experiment (1), the Savannah River Technology Center (SRTC) at the Savannah River Site (SRS) carried out a full-scale test of a "large-diameter" bubbler (LDB) to measure liquid-level and density in high yield stress slurries. The test was the final step in a process to find an instrument that could effectively and economically operate in the existing mixing tank environments. Positive results would lead to implementation of the LDB. This new bubbler replaced two inadequate instruments: an expensive technology, a Holledge probe, which needed replacing twice a year and "standard bubblers," which plugged in as little as four hours of operation.

Three LDBs, at different depths, were tested under highly prototypic conditions from November 27, 1996, to January 23, 1997, using the full-scale test facilities at SRS. The instruments were subjected to 58 days of slurry operation; 14 days of which the slurry was brought to boiling temperatures. The results showed that the LDBs (6.7 cm inside diameter) operated successfully by not plugging with the glass-frit ladened slurry, which was maintained at a minimum temperature of 50°C and at ~102°C during days of boiling.

A recommendation was made to implement the LDB because none of the three bubblers plugged during the test period to the point of compromising liquid-level measurement. However, after a week's operation at boiling temperatures, several inches of a soft sludge built up within the bubbler tubes. This sludge was easily removed in place with high-pressure water. Since completion of this study, four LDBs have been installed in different tanks throughout the Defense Waste Processing Facility at SRS. Their operation has been satisfactory to date.

NOMENCLATURE

cmwc	-	Pressure, Centimeters of Water
DWPF	-	Defense Waste Process Facility
LDB	-	Large Diameter Bubbler
MFT	-	Melter Feed Tank
PHA	-	Precipitate Hydrolysis Aqueous
SME	-	Slurry Melter Evaporator
SpG	-	Specific Gravity
SRAT	-	Sludge Receipt and Adjustment Tank
SRS	-	Savannah River Site
SRTC	-	Savannah River Technology Center
ρ	-	Density
σ	-	Surface Tension

INTRODUCTION

A bubbler is simply a tube that is used to inject a gas into a liquid. It could be used to inject fluids, to mix fluids, or to make a measurement; frequently, a liquid level is measured. A level can be obtained by measuring the pressure at one end of the tube while a slow moving gas flows through and out the other end. The gas is released into the medium, generally a liquid, causing bubbles to form and rise. By knowing the pressure, a liquid height can be determined if the medium density is known. With two bubblers, separated by a known distance, the medium density is also obtainable.

Bubblers have been around for years. Their operation is well understood and because of their simplicity, they can be found throughout industry (2). This is the case for the Department of Energy's Radioactive Waste Facilities at the Savannah River Site (SRS) in Aiken, South Carolina. The added advantage for SRS is a bubbler's robustness to the severe conditions present in the waste tank environments. A tank, depending on the type of waste or its location in the waste process, may contain circulating or stagnant liquids which are radioactivity hot, thermally hot, highly acidic, or highly alkaline. The waste may contain solid particles as small as a micron or as large as several hundred microns and have liquid surfaces that may contain solids, foams, and thick vapors while boiling. Moreover, the radioactive environment requires that all instrumentation must be handled remotely and that tanks can only have penetrations through the top to minimize potential leaks.

The advantage of a bubbler is in its construction, i.e., it is a straight tube with the open end located where a measurement is needed. A straight tube is easily replaced, inexpensive to manufacture, has no moving parts to wear out, and contains no elastomers that break down in radioactive environments. Further, the bubbler instrumentation is a pressure transducer that can be conveniently located outside of the radiation field, facilitating maintenance and calibration.

Bubblers can easily and effectively be used in any of the environmental challenges mentioned above. Unfortunately, since one end of the tube is exposed to the medium, there is a problem that occurs in agitated tanks that contain high yield stress slurries: plugging. Tank agitation forces the slurry to enter the tube. At the interface of the slurry within the tube the air removes moisture causing the yield stress to increase. For standard SRS bubblers, which have an inside diameter between 13-mm and 19-mm, a plug that is approximately 5 cm recessed inside the tube and is 5 cm thick forms. The plug becomes a hard solid that can only be removed by mechanical means (e.g., metal lance).

The plugging problem exists because of the large range of fluid yield stresses of the various waste streams at SRS. As the amount of solids increases in a liquid, the yield stress increases. In some mixing tanks, like the Slurry Mix Evaporator (SME) of the Defense Waste Processing Facility (DWPF), stable operating conditions have slurries, which contain between 45 and 55 wt% solids (35 and 45 wt% insoluble solids). For these solids loadings the yield stress, at 50°C, increases from approximately 1 Pa to 20 Pa, respectively, Fig. 1. [Data are from Table 1 of Ref. 3 and the plastic viscosity ranges from 6 to 30 cP over the same range of solids loading and temperature.] These stresses are from 2 to 10 times greater than some slurries common to chemical industrial, like fine limestone and coal slurries (4) respectively. However, even at these high yield stresses, a bubbler operates satisfactorily. At slurry-gas interfaces, like at the top of the slurry pool or inside the bubbler, the slurry can lose water, causing an increase in solids concentration. As the concentration increases above 55 wt%, the yield stress increases exponentially, e.g., beyond 65 wt% the yield stress is above 100 Pa. At this point, the waste has the consistency of peanut butter, which builds up on the tank walls, equipment at the liquid interface, and inside bubblers. Standard bubblers have plugged in as little as four hours in some mixing tanks, which make them too labor intensive to be practical.

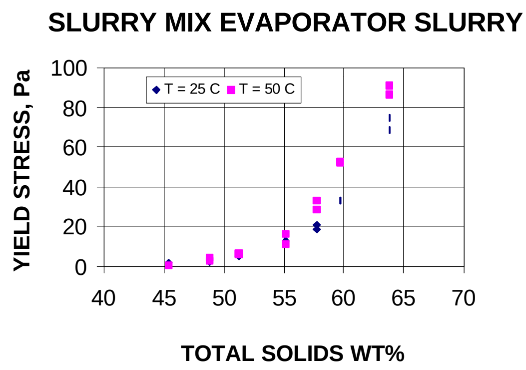


Figure 1. Yield Stress versus Total Solids (Ref. 3)

Several technologies have been tested at SRS to replace bubblers in environments that cause plugging. A search through trade journals will show a wide variety of level-measuring devices (5,6,7,8,9,10,11). Many have been applied to hard to handle liquids (12,13,14,15). To date, none has succeeded, except for some very expensive alternatives. For example, about 10 years ago, bubblers that plugged most frequently were replaced with a similar but more complicated pressure-sensing device, a Holledge Diaphragm Probe. This device works like a bubbler tube in that air flows through a tube and the medium to be measured provides a backpressure. However, instead of air entering the medium, it presses against a diaphragm, which then presses against the medium; the end of this probe is sealed and no liquid can enter. Unfortunately, besides the fact that each probe is relatively expensive its operation was unsatisfactory. There were some problems, such as 1) linearity, 2) high sensitivity to temperature, 3) diaphragm failure from stress, 4) inability to recalibrate once installed, and 5) a diaphragm's limited movement creating a measurement threshold.

Since bubblers do work adequately until they plug, solutions were sought to eliminate or minimize pluggage. Some years ago, several modifications to the standard bubbler were proposed by SRTC of SRS. Seven designs were submitted and four were chosen for small-scale testing. The results of that test (1) concluded that two designs merited full-scale testing. Subsequently, those two designs were tested in a full-scale tank, but only the large diameter bubbler (LDB) was deemed a success.
The success of the LDB was not totally unexpected. Other DOE sites have done studies on a variety of bubblers to minimize plugging problems. Reference 16 concluded, among other things, that increasing the probe size, decreased the frequency of plugging. While using

different slurry mixtures, the bubbler diameter was increased from 6.4 mm to 19.1 mm. The result was that the time to pluggage increased from 1 to 5 hours. Unfortunately, a further increase in bubbler size was not investigated. Others (17) have discussed enlarging bubbler diameters to 25 mm. It appeared that making the bubbler diameter larger might be the solution to developing a non-plugging instrument.

Deciding on how large to make a bubbler diameter was not straightforward since the actual mechanisms to maintain a bubbler plug-free were unknown. However, an assumption was made that if the free surface area within the tube were large enough to allow surface waves, the wave action could assist in preventing sludge build-up. It is known that when a low-density substance is accelerated into a high-density substance (e.g., air and water), surface waves grow the fastest when their length corresponds to the Taylor wave (18). The Taylor-wave length is a function of the interface surface tension, gravity, and the density difference. The two-dimensional theoretical length is $(2\pi[3\sigma/g(\rho_{liquid} - \rho_{gas})]^{1/2})$. For the slurry, the air-liquid surface tension is not well characterized, but for an air-water mixture near the boiling point, the wavelength is approximately 2.8 cm (19). Therefore, it is believed that for bubblers smaller than this dimension, the slurry oscillates in the tube as a plug, with no wave action to prevent pluggage. Because of physical limitations, a tank access port of 7.6 cm, a bubbler with an inside diameter of 6.7 cm was chosen. This paper will give the results of a full-scale test using this large diameter bubbler.

EXPERIMENTAL SETUP

The LDB was made from a 2.5-inch schedule 10 stainless steel pipe (inside diameter of 2.64 inches or 6.7 cm.) Figure 2 shows one of the three bubblers tested. At the end of each bubbler was 30.5-cm long tube that was fed air through a 2.5 cm inside-diameter adapter on the top of the large tube segment. The adapter was fed air from a 6.4-mm steel air tube which led to the air supply and pressure transducer. The length of the large section of tube was chosen based on the small-scale test (1). The slurry was expected to surge between 15 and 25 cm into the tube during steady state operation, due to the energy imparted to the surrounding slurry by tank impellers. To allow the free flow of bubbles from the bottom of the tube, a 3.2-mm deep and 2.6-mm wide notch was made on one side; it is visible in Fig. 2. Three bubblers were tested, and, as shown in Fig. 3, they were located at different vertical heights along a tube structure, referred to as the probe tree. The vertical locations were chosen to coincide with those to be used in the field.

Figure 2. Large Diameter Bubbler: 6.7-cm i.d.

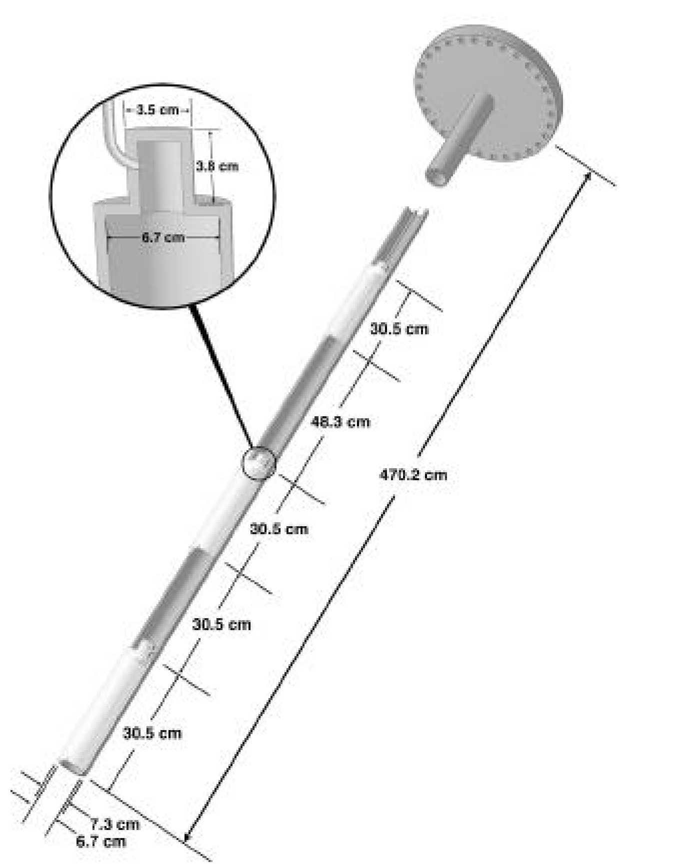


Figure 3. Large Diameter Bubbler Probe Tree

The probe tree was mounted on a large flange, which was bolted to the tank. From the bottom of the flange plate to each probe opening the distance was 470.2 cm, 409.3 cm, and 330.5 cm (which includes the bubble notch just mentioned). The entire probe tree was placed in a large tank opening shown in Fig. 4 on the right side of the tank.

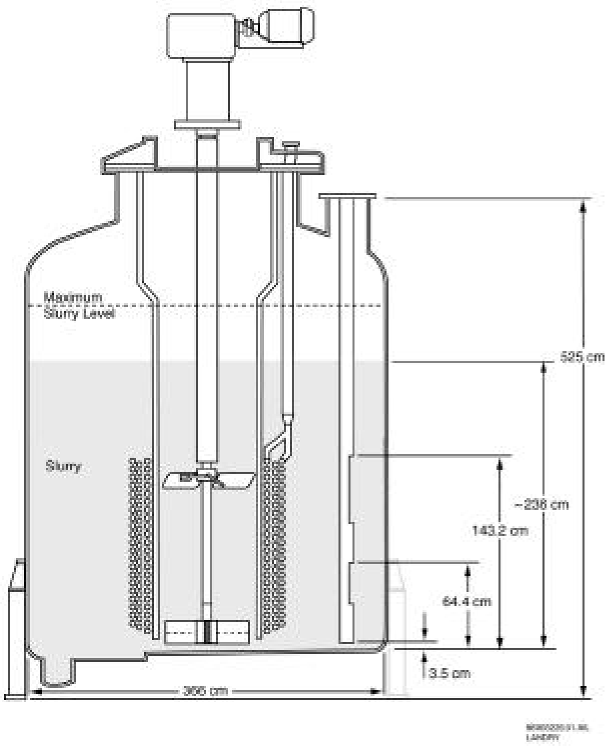


Figure 4. Full-scale Tank with Bubbler Probe Installed

The distance from the top of that opening to the bottom of the tank, at the center, was approximately 473.7 cm. Therefore, the distances between the probe openings and the bottom of the tank were 3.5 cm, 64.4 cm, and 143.2 cm, respectively. During the second week of testing, the probe tree was raised 106.7 cm higher in the tank (for 16 days). The change increased the distance from the tank bottom to the probe openings to 110.2 cm, 171.1 cm, and 249.9 cm, respectively.

The probe tree was raised so that the top-most probe would be held above the slurry and the bottom probes would be at different slurry heights. Some slurry accumulation within the probes was expected after one week of operation. Holding a probe above the liquid was to simulate empty tank conditions after a planned or unplanned down time. The changed positions of the other probes in the slurry was an attempt to accelerate pluggage. Once the probe tree was returned to its original position, after the 16-day period, the hope was that all three probes would continue to function properly.

The full-scale tank, Fig. 4, can hold 45,000 liters of liquid but its normal maximum operating volume is 34,000 liters. For this test it contained 28,000 liters. During the entire test period, the slurry was agitated at 130 rpm (imparting approximately 2.5 hp/1,000 liters of power to the slurry). Steam was maintained in the coils to have a minimum temperature of 50°C. There were several occasions when the steam temperature was allowed to increase so that boiling conditions could be attained. Finally, a vacuum was maintained in the tank at all times. For most of the test period, the vacuum was 18 ±5 cm H_2O.

INSTRUMENTATION AND MEASUREMENT

The main thrust of this work was to determine if the bubbler probes would operate without plugging under prototypic mixing and heating conditions. A total pluggage would prevent airflow to continue in a probe and the air pressure to build up to line pressure; basically a go no-go situation. That is, exact measurements of temperature, level, and gas flow rate were not a priority. The instruments for the temperature and flow rate were standard plant equipment and pressure was measured using simple dial gauges. However for completeness, details of these instruments are given. To specify the three probes used they will be referred to as Probe 1, Probe 2, and Probe 3 to correspond to the upper, middle, and lower positions, respectively; see Fig. 3.

<u>Temperature</u> The full-scale tank used for this test had pre-installed platinum resistance temperature detectors. The readings from those devices were used and had accuracies of better than ±1°C.

<u>AirFlow Rate</u> Each probe had a 0-2.5 standard ft^3/hour (0-20 standard cm^3/second) Wallace & Tiernan rotometer. These instruments are not built for accuracy but for their robustness; they can withstand considerable overpressurization and high temperatures. Under standard plant operation, these meters are set at a flow rate between 4 and 12 cc/s with a meter pressure of 138 kPa. Over the entire range of the instruments a pre- and post-calibration determined the measurement uncertainty to be ±3.5 cc/s (Probe 1), ±6.1 cc/s (Probe 2), ±5.7 cc/s (Probe 3).

<u>Air Pressure</u> Each probe had a 0-200 in.H_2O (0-500 cm H_2O) Noshok round air gauge. During the pre-test calibration, these inexpensive gauges were found to be exceptionally accurate (±5 cm H_2O) and repetitive. Near the end of the test, the gauges were accidentally overpressurized which not only changed their calibration, but also affected their precision. However, the overpressurization had the strongest impact on the accuracies. From a post calibration, the measurement uncertainty degraded to ±25 cm H_2O (Probe 1), ±25 cm H_2O (Probe 2), and ±30 cm H_2O (Probe 3).

TEST PROCEDURE

A general outline of the test procedure is as follows:

- pre-calibrate the instruments
- install the probes in the full-scale tank
- establish 12 cc/s of air to each probe
- monitor probes on an hourly basis
- weekly, remove the probes to document conditions
- after the first period with some days of boiling temperatures: raise Probe 1 out of the slurry
- after the next period with some days of boiling, lower the probe tree to the original height
- after the next period with some days of boiling, document the condition in the morning, replace the probes in the slurry, blow down the probes, remove the probes for documentation
- after the last period with some days of boiling, remove and document
- post-calibrate the instruments

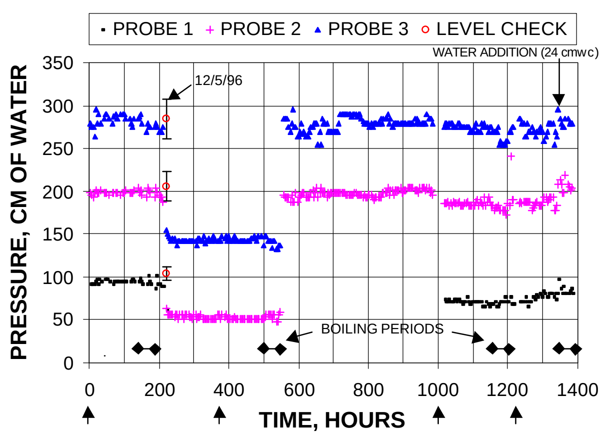
RESULTS

Because of the labor necessary to install and remove the test probes from the full-scale tank, daily sludge accumulations in the probes were not recorded. One week was the minimum time between removals. However, whether the probes were clean of slurry, or not, a week's time was sufficient to allow the slurry to build up in all the probes to the point that some appeared to be plugged.

Figure 5. Pressure data of the Three Bubbler Probes

Figure 5 shows the pressure data from all three probes in centimeters of water. The probes were removed 6 times during the course 1400-hour test; after 200, 400, 550, 1000, 1200, and 1400 hours.

There were several reasons for the removal of the probes but the primary was to document the state of the probes as sludge built up either from one period to the next or



after a cleaning with water. It appeared that the probes had a lot of tolerance to sludge accumulation while still operating satisfactorily; as evidenced from the probe inspections.

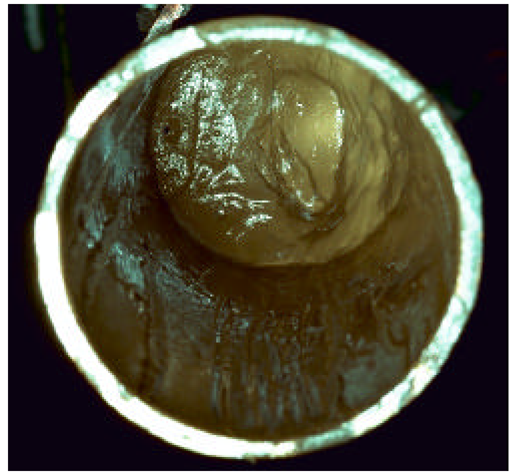


Figure 6. Probe 3 After 200 Hours of Operation, 12/5/96

Figure 6 shows Probe 3 after 200 hours of operation from a clean, new condition. The sludge sits approximately 25 cm inside the 30-cm deep tube. On the right side of the figure an opening exists in the sludge which allowed the probe to function properly. [Note: Probes 1 and 2 had similar sludge accumulations, but because of the way those probes were oriented on the probe tree, photographs were much harder to obtain, see Fig. 3. The lighting was such that the features seen in Fig. 6 are not distinctive. However, an important difference was in the location of the sludge build-up.] For Probe 2, the accumulation was located approximately 15 cm into the tube, and for Probe 1, it was 8 cm into the tube.

The different plug locations existed because heights of submerged waves within the liquid depend upon pressure. (During testing, the liquid level in the tank was approximately 236 cm (see Fig. 4), so the distance from the probe openings to the top of the liquid was 93 cm for Probe 1, 172 cm for Probe 2, and 233 for Probe 3.) The importance here lies in whether liquid level in a tank changes significantly over time. The change in submerged wave heights will cause slurry plugs to occur at different locations. To see the change in wave height with slurry depth a qualitative examination of the data in Fig. 5 shows that as pressure increases (increasing depth), there appears to be more variation in the data. Quantitatively, for the data during first 200 hours of operation, a one-standard deviation of pressure increases from 3 cm H_2O, for lower pressure (Probe 1), to 7.5 cm H_2O, for the higher pressure (Probe 3).

During the next 350 hours, the three probes were raised 107 cm in the tank so that Probe 1 would be above the liquid level and Probes 2 and 3 would experience the different environments of lower liquid levels. This level change was done to simulate a changing liquid level and an empty tank during down times. Figure 5 shows that the probes were still operating successfully between 200 and 550 hours, except for Probe 1, which was above the liquid. The probes were then remove after another 200 hours (for a total of 400 hours) to determine the change in sludge accumulation. The sludge build-up was closer to the tube openings, since they were 107 cm higher in the liquid, see Fig. 7.

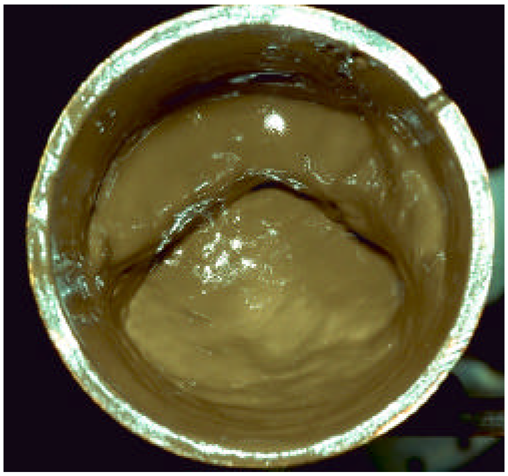


Figure 7. Probe 3 After 400 Hours of Operation, 12/12/96

After the probes were lowered once again (at the 550-hour point), they continued to operate without incident for the next 450 hours. Removing the probes after 1000 hours showed that the sludge accumulations became stable but did not hinder level measurement. Since it appeared that the probes were not going to plug, an attempt was made to determine if the sludge could be removed remotely. Therefore, the probes were replaced in the tank and blown down with pressurized water (620 kPa) for five minutes. Figure 8 shows that most of the sludge was removed. This result is significant since the sludge-plugs that occur in standard bubbler tubes are impossible to remove remotely. That is, the bubblers have to be removed from the tank and cleaned with a metal lance. That method is very costly in a radioactive environment. After cleaning the bubblers remotely they were operated for another 200 hour (for a total of 1200 hours). Once again, the sludge built up internally to the probes, but not to the point of preventing level measurements to be made. See Fig. 5 at 1200 hours.

After 1200 hours of operation the probes were removed for inspection. Figure 5 shows that level readings were not affected by the sludge build-up but Fig. 9 shows that most of the Probe 3 opening to be spanned with sludge.

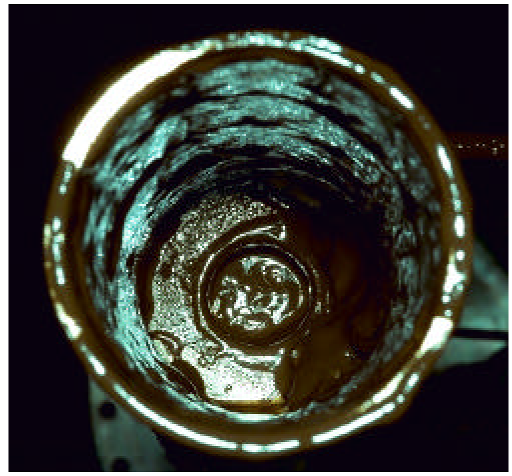


Figure 8. Probe 3 After a Water Blow-down, 1/7/96

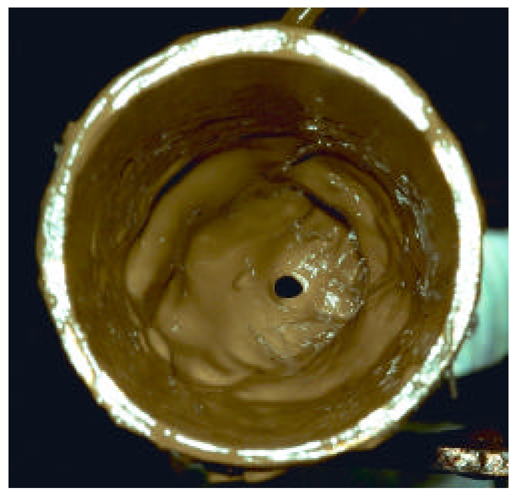


Figure 9. Probe 3 After 1 Week from a Cleaning, 12/12/96

Outside of the increased variance in the data, as a probe is located deeper in the slurry, these three probes correctly indicated the liquid level and never experienced an onset of plugging. To verify that the probes were measuring the slurry level accurately, an independent level measurement was made by using a dipstick on 12/5/96. That measurement indicated a liquid level of 236 cm. By knowing the position of each probe, the approximately density of the solution (SpG~1.3±0.05), and the approximate pressure above the liquid (p~ -18±5 kPa), each probe's depth was calculated. That independent reading is shown on Fig. 5 as the open circles with error bars. For each probe, the data fall within the uncertainty of the level indication. Another way of checking the data is by comparing the pressure readings between probes to the known vertical separation of those probes. For the Probes 1 and 2, Fig. 3 shows the distance between openings to be

48.3 + 30.5 = 78.8 cm. When accounting for the SpG, then the distance is 78.8 x (1.3 ±0.05) = 102 ±4 cm. Fig. 5 shows the pressure readings to be approximately 198 - 94 = 104 cm. For the Probes 2 and 3, Fig. 3 shows the distance between opening to be 30.5 x 2 = 61.0 cm. When accounting for the SpG, then the distance is 61.0 x (1.3 ±0.05) = 79 ±3 cm. Fig. 5 shows the pressure readings to be approximately 280 - 198 = 82 cm. The probes appeared to be indicating the probe spacings correctly.

Notes on the data shown in Fig. 5:

1. Dates on the graph indicate when the probes were removed from the tank. Specifically on 11/27/96, the test began and on 12/5/96, 12/12/96, 12/19/96, 1/7/97, 1/16/97, the probes were removed for documentation, and on 1/23/97 the test ended.
2. Boiling conditions (T~102°C) existed for 14 days of the 58-day test. The specific times are indicated on Fig. 5 by the small diamond-ended lines on the bottom of the graph. On all of the remaining days the liquid was maintained at T~50°C.
3. Airflow rates to the probes were held relatively steady at all times. The flow rate was 11 cc/s (std.dev. ~1.6 cc/s: N=243) for Probe 1, 12 cc/s (std.dev. ~1.6 cc/s: N=325) for Probes 2 and 3. Since they were all metered at a pressure of 138 kPa, the flow rates at standard conditions were 20 and 23 cc/s, respectively.
4. Near the end of the test on 1/21/97, approximately 1900 liters of water were added to the tank to make up for evaporative losses. The water addition amounted to approximately an 18-cm increase in slurry height, which translates to a 24-cm increase in water pressure.
5. There are several periods when data for Probe 1 are not shown. As previously explained, after the first 200 hours of operations, the entire set of probes was raised 107 cm. The vertical-height change was done for two reasons: 1. Probe 1 was held above the slurry level so that the first week's worth of accumulated slurry could dry and possibly cause a more severe pluggage to occur once it was lowered back into the slurry. Holding the probe above the slurry was to represent either a planned or unplanned down time with a drained tank to see if the probe would recover after a start-up, and 2. Probes 2 and 3 were raised in the slurry to represent a changing tank level. Sludge would then begin to build up below previous accumulations inside the probes. The added accumulations could have a tendency to accelerate pluggage. (The probes were raised instead of lowering slurry level because the full-scale test vessel inventory of 28,000 liters could not be easily maneuvered. Between 200 and 550 hours, the pressure transducer of Probe 1 was exposed to the 18 cm H_2O of vacuum above the liquid; no readings were taken. Between 550 and 1000 hours, Probe 1 returned to reading a steady slurry level, but the accuracy of the simple pressure gauge used was significantly affected by the vacuum. The data were left off Fig. 5 because they confound the data from the other two probes. After 1000 hours, all pressure transducers were rezeroed so Probe 1 data can again be seen in the Fig. 5.

CONCLUSION AND RECOMMENDATION

Three Large Diameter Bubbler probes were operated in a well mixed slurry that had a solids content between 50 and 55 wt% with a bimodal distribution of particulates (glass frit ~100 μm and metallic oxides ~1 μm). In the bulk of the slurry, the plastic viscosity varied between 10 and 30 cP, and the yield stress, between 5 and 15 Pa. At the air-slurry interfaces within the bubblers, where air removes moisture from the slurry, the yield stress increases by more than an order of magnitude. The LDB probes operated for 44 days at 50°C and 14 days at boiling (~102°C) without plugging.

While the 6.7-cm inside diameter bubblers did not indicate impaired level measurements due to the sludge that built up inside the tubes, the sludge can easily be removed with several minutes of washing with water. A weekly blow-down with water was recommended to avoid unwanted pluggage.

Since the completion of this test, the Defense Waste Processing Facility has replaced existing level instrumentation with LDBs in four mixing tanks. Further, the LDB will replace all other expensive level probes in tanks where plugging has been a problem and when replacement is warranted.

ACKNOWLEDGMENTS

We would like to thank the WSC personnel who assisted us. From the Immobilization Technology Section: Bill Holtzcheiter for allowing us to use the test facilities, Chris Randall, who supervised the work and obtained funding, Nick Odom, who assisted in doing the experiment, and to all the many operators who spent hours monitoring the experiment, taking data, and safely applying their skills to install and remove equipment. From the Experimental Thermal Fluids Laboratory: Dave Muhlbaier, who supervised the work, and Steve Hargett and Jerry Corbett, who provided drafting and engineering expertise. From Publications & Media Services: thanks goes to Steve Ashe and Bruce Boulineau for their photograph expertise and Ed Landry for the professional illustrations. From the Defense Waste Processing Facility: Joe Ortaldo for supporting this project, and John Occhipinti for his invaluable information concerning the actual mixing tank operation and needs. This work was funded by the U.S. Department of Energy under Contract DE-AC09-96SR18500

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